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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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ABSTRACT

In the absence of wave damping the momentum of a weak cold beam can be clamped while the wave amplitude increases secularly in time. When wave damping is present a nonlinear equilibrium is attained in which the beam evolves into a singular charge clump which drifts at constant velocity through the plasma.

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It is well known that when a low density fast electron beam is injected into a background plasma it triggers an electrostatic two-stream instability. It has been shown both theoretically[1,2] and experimentally[3,4] that this instability leads to the growth of a nearly monochromatic electron plasma wave (single mode) whose amplitude saturates by trapping the beam electrons within its potential troughs. The process of beam trapping is of interest to basic plasma physics studies since it provides an example where coherent nonlinear processes play a dominant role, thus entering the domain where the familiar quasilinear theory based on the random phase approximation is not applicable. On the practical side, saturation by beam trapping limits the maximum energy that can be extracted in travelling wave tube (TWT) devices used extensively to generate microwave radiation.

This letter illustrates the changes produced on the dynamics of beam trapping when an external DC electric field E_o is applied to the beam particles. This problem is of interest for various reasons: (1) it provides an idealization of the coherent interaction of a population of runaway electrons with collective modes, (2) it explores the possibility of enhancing the efficiency of energy extraction out of beam devices, (3) it simulates the effect of low frequency turbulence on beam nonlinearities. The major effects found in this study are: (1) the beam can be clamped in energy with the momentum push transferred to the wave, (2) the normal beam saturation level can be significantly enhanced by $E_o \neq 0$ (DC to AC conversion), (3) a dynamic Bernstein-Greene-Kruskal (BGK) equilibrium[5] is attained when wave damping is included.

The present study is based on the formulation of the small cold beam problem given by O'Neil, et al.[1] The essence of the procedure consists of describing the behavior of the background plasma analytically through a

linear dielectric, and following the exact orbits of the beam electrons in a computer, i.e., the beam is discretized into N particles. The velocity v_j and position x_j of the j particle is obtained from

$$m \frac{d}{dt} v_j = eE_o - eE(t)\exp\{i[kx_j(t) - \omega_o t]\} + \text{c.c.} \qquad (1)$$

where e, m refer to the electron charge and mass, k is the wavenumber of the fastest growing wave, ω_o is the frequency of the wave in the absence of the beam, and $E(t) = E(0)\exp[-\, i \int_o^t dt'\delta\omega(t')]$ refers to the slowly changing wave amplitude with $\delta\omega$ being the complex frequency shift. The wave amplitude is determined self-consistently from Poisson's Eq.

$$\left(\frac{\partial\varepsilon}{\partial\omega}\right)_o \frac{d}{dt} E = \frac{4\pi e n_b}{Nk} \sum_j \exp\{-\, i[kx_j(t) - \omega_o t]\} \qquad (2)$$

where n_b is the beam density and ε the linear dielectric of the background particles, i.e., $\varepsilon(k,\ \omega_o) = 0$.

The physics associated with $E_o \neq 0$ is made clear by the two conservation laws associated with Eqs.(1) and (2)

$$\frac{d}{dt}\left[n_b \sum_j \frac{mu_j}{N} + k\left(\frac{\partial\varepsilon}{\partial\omega}\right)_o \frac{|E|^2}{4\pi}\right] = e n_b E_o \qquad (3)$$

$$\frac{d}{dt}\left[n_b \sum_j \frac{mu_j^2}{2N} + 2\mathrm{Re}(\delta\omega)\left(\frac{\partial\varepsilon}{\partial\omega}\right)_o \frac{|E|^2}{4\pi}\right] = e n_b \sum_j \frac{u_j}{N} E_o \qquad (4)$$

with $u_j = v_j - \omega_o/k$. For $E_o = 0$, Eqs.(3) and (4) are satisfied by balancing the increase in wave amplitude with the simultaneous recoil and trapping of the beam. However, for $E_o \neq 0$ Eq.(3) indicates that the total momentum of the beam-wave system must increase secularly in time. There are two ways to satisfy this constraint: (1) the beam momentum increases secularly in time with the wave amplitude essentially constant, i.e., the beam runs away,

and (2) the beam momentum remains clamped while the wave amplitude increases secularly. A given state, beam or wave runaway, is determined by the value of E_o. The threshold value separating the two states is obtained naturally from this formalism because it can be fully scaled. After going through the scaling the equation of motion shows that beam clamping is possible if $E_o < E_T$, $E_T = m\Omega^2/ek$, $\Omega = [(n_b/n_o)\ \omega_p^2/(\partial\varepsilon/\partial\omega)_o]^{1/3}$, and ω_p is the electron plasma frequency of the background plasma of density n_o. E_T is the saturation amplitude for $E_o = 0$. Physically, if $E_o > E_T$ the wave can not cancel the external force, thus leading to a runaway beam. For $E_o < E_T$ the external push prevents the beam from recoiling, thus the wave continues to be driven by the beam.

To verify the existence of the two runaway states and their dependence on E_o/E_T we have solved numerically for the time evolution of the system using the scaled versions of Eqs.(1), (3), (4). Figure 1 exhibits the time evolution of the scaled amplitude ($A \equiv E/E_T$, $\tau = \Omega t$) and the momentum of the beam $P \equiv \sum ku_j/N\Omega$. The DC field is turned on at $\tau = 10.0$ at a value $E_o/E_T = 2.0$. It is seen that the amplitude saturates at a level slightly larger than that for $E_o = 0$, but it does not execute the typical trapped particle oscillations because all the beam electrons are untrapped, as indicated by the secular increase in P. In this case the beam runs away, as expected, and the wave-particle resonance is detuned for this particular mode. Of course, other modes with smaller k are expected to be excited as the beam accelerates.

Figure 2(a) shows the time evolution of the wave amplitude for the case $E_o/E_T = 0.5$. As predicted, the wave is observed to grow secularly to large amplitude. The $E_o = 0$ result is included for comparison. Figure 2(b) shows the evolution of the frequency shift W. An

examination of phase-space (not shown) indicates that the bulk of the beam electrons (> 90%) is trapped within the troughs of the growing wave, as is evident in the amplitude oscillations of Fig. 2(a). In addition, a small secondary runaway beam is created; it arises from the few particles (< 10%) which spill over the potential well as the beam rotates in phase-space.

As indicated by the conservation laws, the beam-wave system can not attain a steady state for $E_o \neq 0$. To reach a steady state an external dissipation mechanism must be present, e.g., plasma heating, wall heating, radiation leakage. To investigate this effect we introduce a scaled damping factor $\Gamma/2$ whose origin need not be specified. The scaled conservation laws become

$$\frac{d}{d\tau}\,[P + A^2] = (E_o/E_T) - \Gamma A^2 \tag{5}$$

$$\frac{d}{d\tau}\,[K + 2WA^2] = (E_o/E_T)P - 2W\Gamma A^2 \tag{6}$$

where W is the real part of the scaled $\delta\omega$ and K is the scaled kinetic energy of the beam. A steady state solution of Eqs.(5) and (6) is $A = (E_o/E_T\Gamma)^{\frac{1}{2}}$, $P = W = 0$. However, to satisfy $P = 0$ for all τ, the equation of motion demands that $E_o/E_T = A \sin (kx_j-\theta)$ for some fixed phase factor θ. Since this constraint must hold for all j it follows that all beam particles must occupy the same position, i.e., the beam must evolve into a singular charge clump whose momentum remains fixed although an external electric field is being applied. This unusual nonlinear state is an example of a dynamic BGK equilibrium in which the beam-clump acts as an intermediate agent that transfers the momentum push of E_o, through the wave, to those mechanisms that give rise to Γ. The self-consistency of the clump position and the amplitude demand that $(E_o\Gamma/E_T)^{\frac{1}{2}} < 1$ for this steady-state to exist.

Figure 3 illustrates the evolution of A and W for a case $E_0/E_T = 0.5$, $\Gamma = 0.05$, satisfying the existence criterion. It is seen that the runaway wave saturates and approaches asymptotically the predicted steady state value of $\sqrt{10}$. The frequency shift approaches $W = 0$, as is required for the steady state. The evolution of the clamped beam toward a singular charge clump is demonstrated in the phase space plots shown in Fig. 4. For $\tau = 25.0$ we see the pattern associated with the early wave runaway process typical of the $\Gamma = 0$ behavior shown in Fig. 2. However, for late times ($\tau = 85.0$) the bulk of the beam particles form a singular clump, as predicted. It is also observed that a small secondary runaway beam is generated, but its presence does not affect the attainment of the singular equilibrium. Of course, physically one expects that the singular charge clump is limited in extent in a real system due to the strong repulsive forces that arise, such an effect is not included in the present formulation.

In summary, the present study shows that when the exact beam dynamics are followed it is possible for a runaway beam to become clamped. This result confirms an earlier prediction[6] of this effect based on a spatially averaged formalism. The clamping process generates a runaway wave, thus suggesting an efficient method for converting DC to AC energy. When wave damping is present, a dynamic BGK equilibrium is approached in which the beam evolves into a singular charge clump that drifts through the plasma at constant velocity. The stability and limiting factors of this state require further study.

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FIGURE CAPTIONS

FIG. 1 Time evolution of the scaled wave amplitude A and average beam momentum P in the beam runaway regime ($E_o > E_T$), for $E_o = 2.0\ E_T$, $\Gamma = 0$.

FIG. 2 (a) Time evolution of the scaled wave amplitude A and (b) frequency shift W in the clamped beam regime ($E_o < E_T$), $E_o = 0.5\ E_T$, $\Gamma = 0$. Result for $E_o = 0$ is included for comparison.

FIG. 3 Evolution toward the dynamic BGK equilibrium in the presence of wave damping, $E_o = 0.5$, $\Gamma = 0.05$.

FIG. 4 Phase-space plot showing the formation of a singular charge clump, $E_o = 0.5$, $\Gamma = 0.05$, (a) $\tau = 25.0$, (b) $\tau = 85.0$.

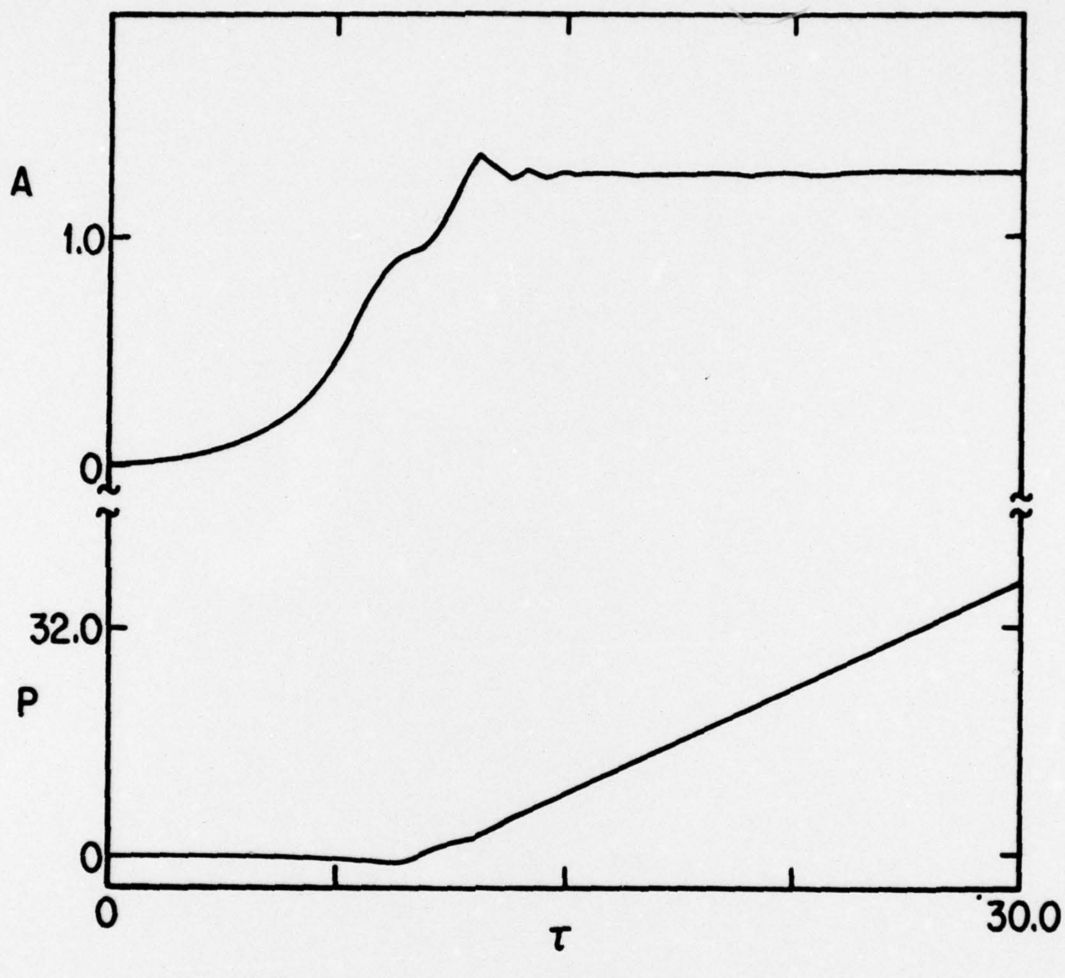

FIGURE 1

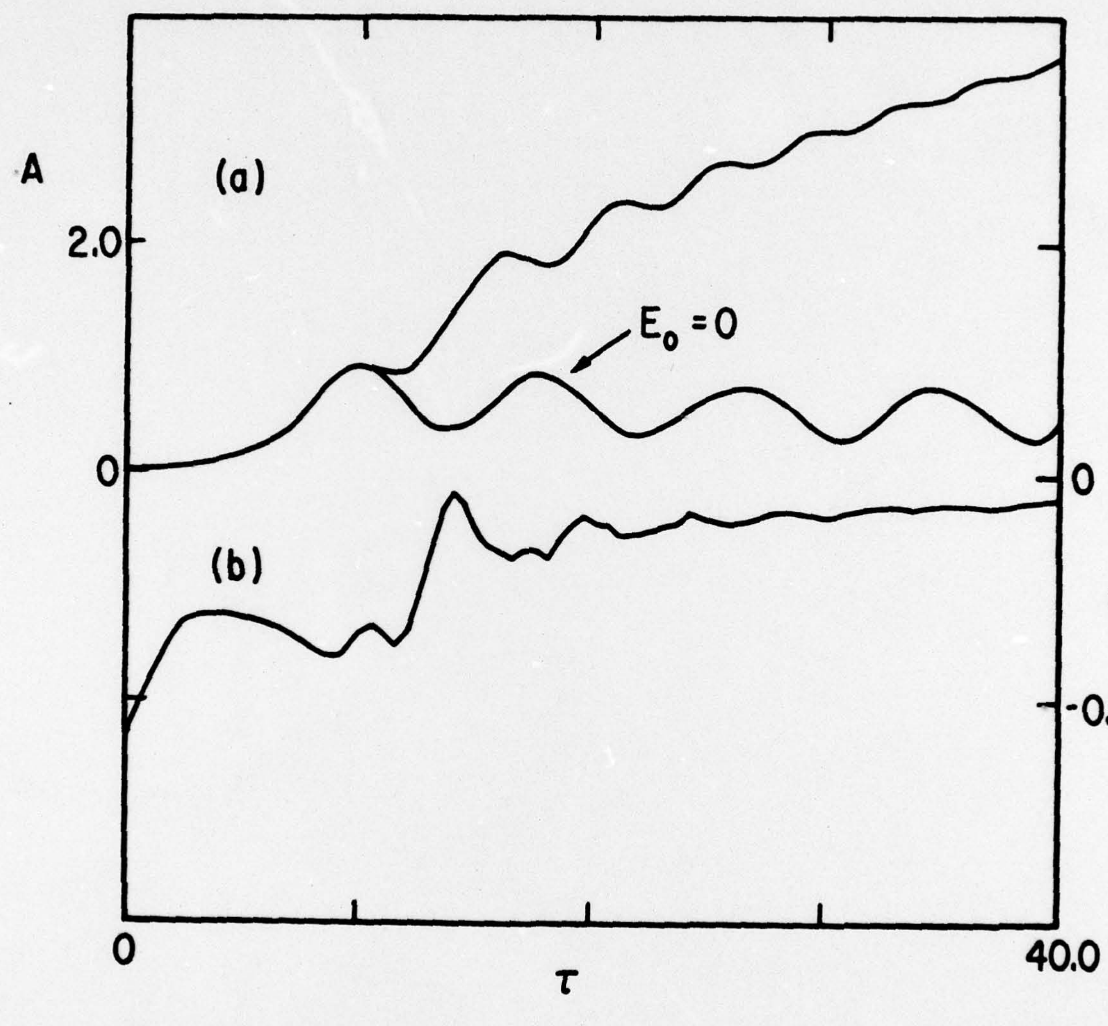

FIGURE 2

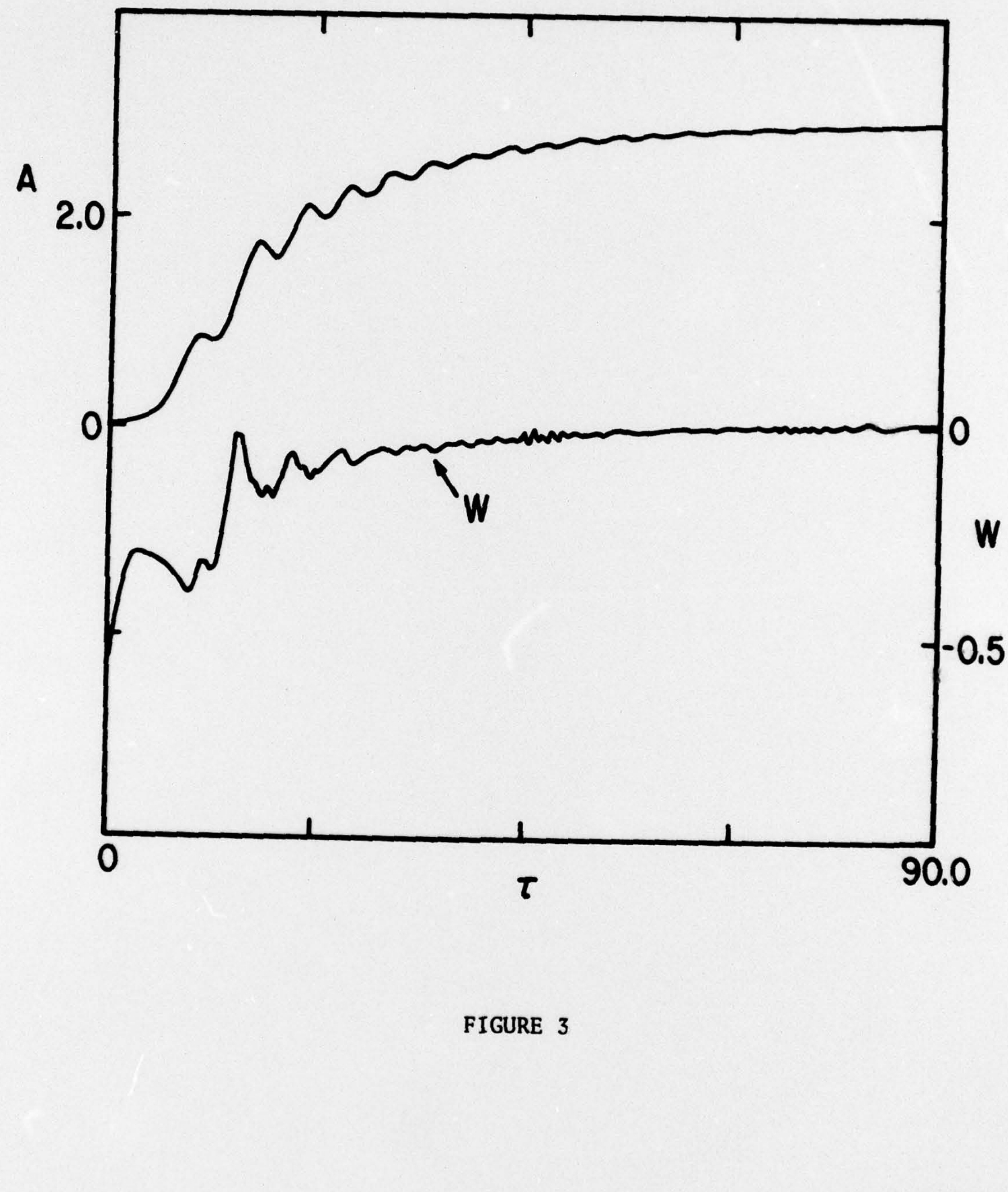

FIGURE 3

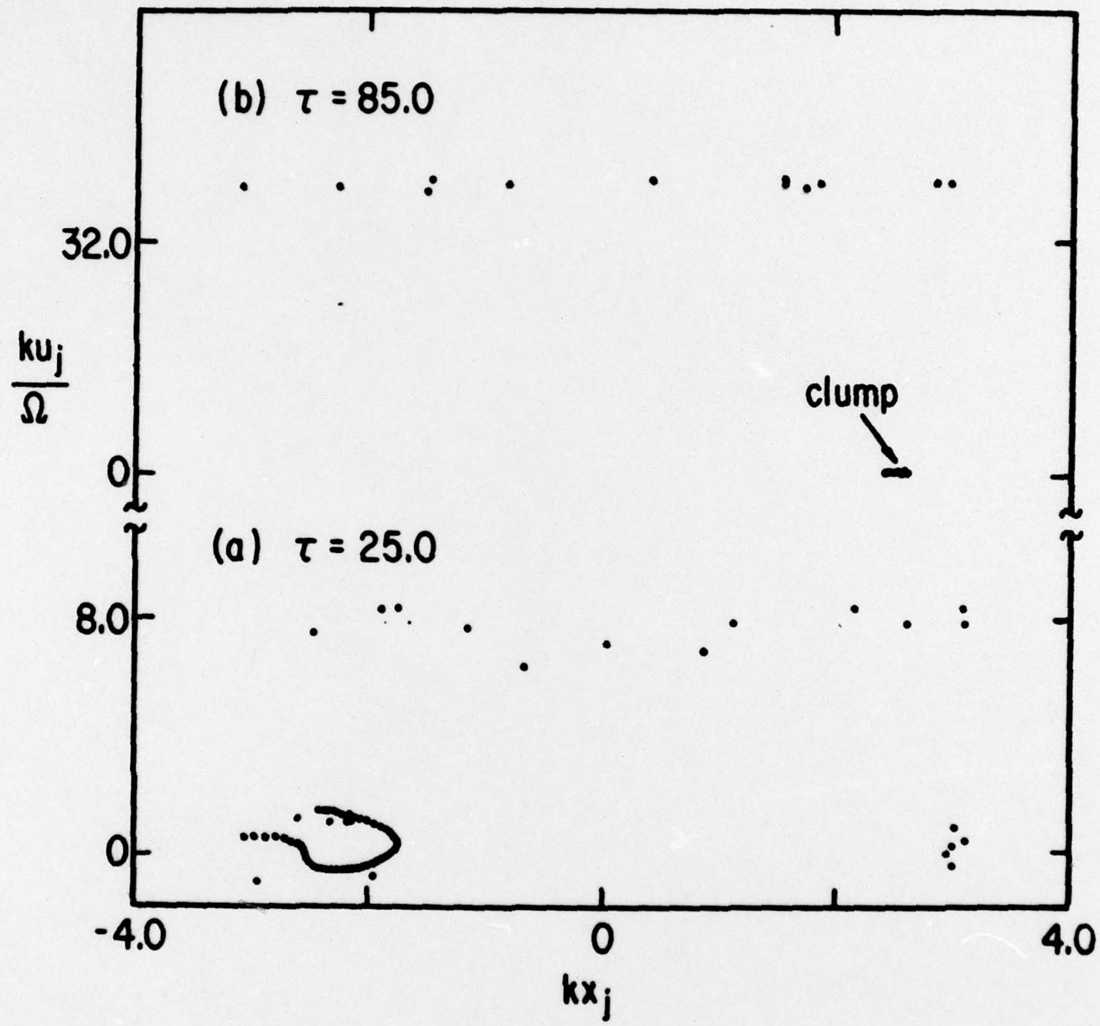

FIGURE 4

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